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RESEARCH ARTICLE

# Fine particle transport dynamics in response to wood additions in a small agricultural stream

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## Abstract
Wood additions to streams can slow water velocities and provide depositional areas for bacteria and fine particles (e.g., particulate organic carbon and nutrients sorbed to fine sediment), therefore increasing solute and particle residence times. Thus, wood additions are thought to create biogeochemical hotspots in streams. Added wood is expected to enhance in-stream heterogeneity, result in more complex flow paths, increase natural retention of fine particles and alter the geomorphic characteristics of the stream reach. Our aim was to directly measure the impact of wood additions on fine particle transport and retention processes. We conducted conservative solute and fluorescent fine particle tracer injection studies in a small agricultural stream in the Whatawhata catchment, North Island of New Zealand in two reaches—a control reach and a reach restored 1-year earlier by means of wood additions. Fine particles were quantified in surface water to assess reach-scale (channel thalweg) and habitat-scale (near wood) transport and retention. Following the injection, habitat-scale measurements were taken in biofilms on cobbles and by stirring streambed sediment to measure fine particles available for resuspension. Tracer injection results showed that fine particle retention was greater in the restored compared to the control reach, with increased habitat-scale particle counts and reach-scale particle retention. Particle deposition was positively correlated with cobble biofilm biomass. We also found that the addition of wood enhanced hydraulic complexity and increased the retention of solute and fine particles near the wood, especially near a channel spanning log. Furthermore, particles were more easily remobilized from the control reach. The mean particle size remobilized after stirring the sediments was ~5 μm, a similar size to both fine particulate organic matter and many microorganisms. These results demonstrate that particles in this size range are dynamic and more likely to remobilize and transport further downstream during bed mobilization events.

**KEYWORDS**
fine particles, immobilization, remobilization, restoration, stream, transient storage, transport, wood

# 1 | INTRODUCTION

Wood is a key component in forested streams, playing an important ecological and physical role in creating step-pool profiles, enhancing habitat heterogeneity, retaining organic matter, and changing water velocity (Beckman & Wohl, 2016; Krause et al., 2014; Sawyer & Cardenas, 2012). Invertebrates use wood as a source of food, a substrate for egg laying and as physical habitat that provides cover and refuge (Flores et al., 2017; Lester & Boulton, 2008). In many cases, accumulations of wood are hot spots of invertebrate diversity (Pilotto, Bertoncin, Harvey, Wharton, & Pusch, 2014; Pilotto, Harvey, Wharton, & Pusch, 2016). Wood is also used as refuge and food source for fish (Baillie, Hicks, van den Heuvel, Kimberley, & Hogg, 2013). Unfortunately, wood has been removed from many stream channels, both directly and indirectly via forest clearing in upstream catchments. Consequently, much of the habitat complexity and the invertebrate diversity and production supported by in-stream wood have disappeared.

Large wood, defined as logs with a diameter >0.1 m and length >1 m (Gregory, Boyer, & Gurnell, 2003), can increase surface water-groundwater exchange, increase in-stream residence times by slowing water velocities and provide high depositional areas for particulate organic matter (Briggs, Lautz, McKenzie, Gordon, & Hare, 2012). Sawyer and Cardenas (2012) through simulated streamlines around a channel-spanning log, demonstrated that the addition of a channel-spanning log increased hyporheic exchange, which in turn may create biogeochemical hotspots in streams that may increase the potential for local nutrient cycling and processing (Blaen et al., 2018; Briggs, Lautz, Hare, & González-Pinzón, 2013). Stream restoration practices such as adding gravel cross-vanes (Smith & Prestegaard, 2005; Wohl et al., 2005) or altering the underlying sediment hydraulic conductivity (Herzog, Higgins, & McCray, 2015; Herzog, Higgins, Singha, & McCray, 2018) may require extensive time and money, while wood additions can be easily implemented by land owners, such as farmers. Therefore, large wood additions as a restoration tool shows promise to develop refuge areas needed for invertebrates and fish, while also improving biogeochemical processing in streams.

Fine particles, such as particulate organic carbon, fine sediment, and particulate nutrients are important to stream ecosystem functioning. It is well known that restoration with large wood increases coarse organic matter retention (Elosegi, Díez, Flores, & Molinero, 2017; Flores, Larrañaga, Díez, & Elosegi, 2011; Tank, Rosi-Marshall, Griffiths, Entrekin, & Stephen, 2010), but there is limited information available on how fine particle transport and retention are impacted by wood additions. Specifically, it is unknown if the balance between fine particle immobilization and remobilization processes will lead to an overall increase in retention, or less retention due to the possibility of a higher likelihood of remobilization. The altered hydrological processes in streams with added wood may also enhance the deposition of fine particles into sediments and onto biofilms on cobbles, previously shown to be important transient storage areas for fine particles that extend particle residence times for months to years, altering the exchange of oxygen, carbon, and nutrients into the sediments (Drummond et al., 2015; Drummond, Larsen, González-Pinzón, Packman, & Harvey, 2017; Roche et al., 2017). Fine particle immobilization is expected to increase in streams with added wood and differ based on orientation of the wood in the stream. However, the interactions between particle immobilization and remobilization in these systems have not yet been assessed.

The objectives of this research were to determine if wood additions to a small agricultural stream: (a) enhances in-stream heterogeneity, resulting in more complex flow paths, and increased retention of fine particles; (b) increases transient water storage, allowing for potentially greater nutrient cycling and biogeochemical processing; (c) whether these processes change with the orientation of wood; and (d) alters the remobilization of fine particles from streambed sediments. We co-injected a conservative and fine particle tracer into two stream reaches and measured fine particle transport within surface waters and immobilization and retention within transient storage areas (i.e., streambed sediments and biofilm on cobbles). We then stirred streambed sediment and measured the size and number of fine particles available for resuspension in response to a bed mobilizing event.

# 2 | MATERIALS AND METHODS

## 2.1 | Study site description

Whatawhata Research Station was established in 1949 and is located in the Waikato Region of New Zealand, west of Hamilton city in the North Island (−37.777S 175.070E). The hills throughout much of the Whatawhata Research Station were deforested around 90 years ago to establish pastoral agriculture. Since 2000–2001, land use and management have changed, including conversion of the steepest land to plantation forestry, restoration of indigenous forest, exclusion of livestock from streams, erosion control and improved farming practices (Quinn, Croker, Smith, & Bellingham, 2009). Tracer injections were conducted in the Kiripaka Stream at the Whatawhata Research Station (−37.784S 175.068E) in two similar reaches (control and impact) approximately 150 m apart (Figure 1a,b).

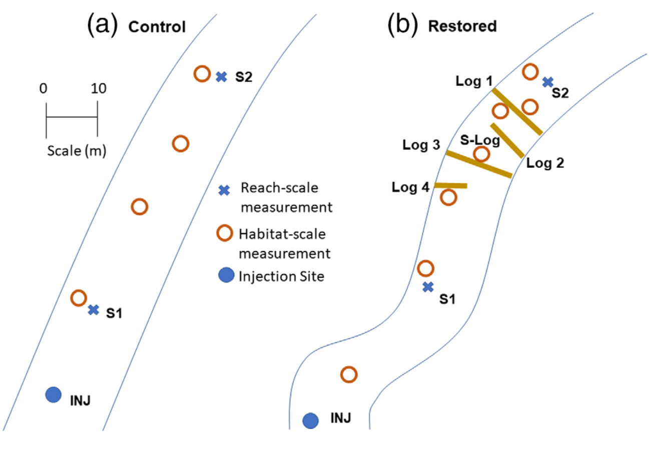


**FIGURE 1** Schematic of the injection experiment and reach-scale and habitat-scale sampling locations in the (a) control and (b) restored reaches

Average wetted width is around 2 m and the streambed is composed of both fine (silt) and larger coarser (gravel, cobbles) sediments. One year prior to the tracer experiments, the downstream (impact) reach was restored using wood additions. Hereafter this is referred to as the restored reach, although only the lower part of the reach contains added wood (Figure 1b). The geometry of the stream and wood additions are shown in Figure 1b. The wood additions comprised four tree-fern log structures placed in the stream. Tree-fern logs are often found naturally in NZ streams and were chosen because they are relatively inexpensive and easy to cut and manipulate. Two wood configurations were used: logs angled at approximately 30° to the flow, and channel spanning sill logs set at 90° to the flow. Two sections of log, approximately 0.4 m long and 0.2 m in diameter, were tied to both ends of the sill logs, which spanned the full wetted width of the stream. The structures were staked into the substrate with hard-wood poles. The logs used for the 30° addition were approximately 1.5 m long and had two 0.4 m lengths tied to just one end to act as a pseudo-root-wad. These structures were staked into the stream bank, with the opposite end facing downstream. The angled structures spanned approximately 65% of the stream width.

## 2.2 | Experimental design—Tracer injection and sampling

We injected a conservative solute (seawater) with an inert fluorescent particle tracer into both the control and restored reaches. The control reach length was 36.34 m with sampling sites S1 and S2 at 13.15 m and 36.34 m downstream of the injection site, respectively (Figure 1a). The restored reach with the emplaced logs was 44.16 m total length, with sampling sites S1 and S2 at 24.59 m and 44.16 m, respectively (Figure 1b). An additional sampling site to test habitat-scale solute and fine particle retention directly behind a channel spanning log was placed 38.21 m downstream at Log 3, referred to as S-Log. The injection took place on March 22, 2013 in the restored reach and on March 26, 2013 in the control reach. The discharge measured at the Kiripaka flow gauge (located just upstream of the control reach) was 12.63 L/s on March 22 and 12.20 L/s on March 26 at the time of injections.

To prepare the injectate, 11 L of stream water and 265 g of pink fluorescent fine particles (Dayglo® Fluorescent AX Pigments-Aurora pink, Cleveland, OH) were added and dispersed with an overhead paint mixer. Dispersant (5 g $L^{-1}$ of sodium hexametaphosphate) was added to facilitate wetting and dispersion of the (slightly hydrophobic) fluorescent fine particles. The fluorescent fine particles ranged in size from 1 to 10 μm in diameter, averaging ∼4 μm as measured by an EYE TECH laser particle analyser (Ankersmid, Eindhoven, Netherlands). The particle density was 1.36 g $cm^{-3}$. After the fluorescent fine particles were dispersed, and immediately prior to the injection, 9 L of seawater was added to the injection bucket to provide a solute signal.

The injectate was pumped for 5 min from the mixing barrel at a rate of 0.054 L/s into the stream via a diffuser to evenly distribute the tracers across the centre of the stream (Figure 2). In total, 16.2 L of the injectate was added in the restored reach from 11:30 to 11:35. In the control reach, the pump malfunctioned and was very low during the addition from 11:45 to 11:50. The injection was, therefore, repeated at the correct injection rate from 12:01 to 12:06, adding a total of 20 L of injectate to the stream. A seawater tracer injection was repeated for a third time from 13:26 to 13:31, and this solute data was used in the reach-scale modelling and calculations (Section 2.5 and 2.6) to avoid any background interference with the first malfunctioned injection. This was not an issue for the fine particle tracer as the detection limit is higher above background than seawater and therefore the first particle injection did not interfere with the second. Tracers were monitored in-stream at downstream sites using sondes and auto-samplers (Figure 2b), with S1 and S2 in the channel thalweg and S-Log immediately downstream of a channel-spanning log (Log 3, Figure 1b and 2c). The sondes recorded a measurement every 30 s and the auto-samplers took a sample every 5 min up to 110 min in the restored reach and 88 min in the control reach.

## 2.3 | Streambed sediment and cobble biofilm sampling

Fine particles were measured in biofilms on cobbles throughout the stream reach following the in-stream sampling. At each site four


**FIGURE 2** Tracer injection experiments (a) solute and particulate tracers injected through a diffuser to evenly distribute the tracers across the center mixing area of the stream, (b) Auto-samplers and water quality logging equipment installed prior to the injection at two in-stream locations in channel thalweg to measure reach-scale solute and fine particle transport and retention. The auto-sampler intakes were positioned close to the conductivity sensor. Photo taken during the 5 min injection to demonstrate complete in-stream mixing of tracers throughout the reach. (c) Auto-sampler and water quality logging equipment installed immediately downstream of an emplaced log (S-Log) in the restored stream to measure habitat-scale surface storage of solute and fine particles

cobbles were collected. In the restored reach, four additional samples were taken near the wood (downstream and upstream of log 1, upstream of log 4 and downstream of log 3). Therefore, a total of 32 and 16 cobbles were taken at the restored and control reaches, respectively. The biofilm was scraped from the exposed surface of each cobble into a sample container using deionized water, which resulted in a biomass slurry. Five millilitres of the biomass slurry was removed to use for fluorescent particle counts and the remainder was used to estimate biomass following the ash free dry mass method (Section 2.4). The surface area of each cobble was estimated by weighing tin foil cut outs that covered each cobble and multiplying this weight by a calibration curve of foil area to weight.

Fine particles available for remobilization were sampled following a modified method of Petticrew, Krein, and Walling (2007), which involved pushing a 23.5 cm diameter bucket into the stream bed to form a seal and isolate the flow of the surrounding water, vigorously stirring with a stick within the enclosed container, and then collecting a sample of the resulting suspension. The volume of sediment displaced from the streambed during the disturbance was calculated by multiplying the average difference of five depth measurements before and after stirring by the known bucket dimensions.

## 2.4 | Laboratory analysis of tracer samples

A flow cytometer (Becton Dickson FACS Calibur) was used to analyse fluorescent fine particle concentrations in the surface water samples, using the software program CELLQuest Version 3.3. During the flow cytometer counting process, forward scatter, side scatter and fluorescence parameters were displayed on $\log_{10}$ scale plots to include the range of size and fluorescence of the fluorescent fine particles. The sample was run at a flow rate of ~60 μl min$^{-1}$ for 2 min. TruCount beads were added to each sample in order to determine the exact volume analysed. Each sample contained 800 μl, consisting of 750 μl of surface water and 50 μl of Trucount bead suspension (prepared by diluting1 Trucount tube, $\sim 5 \times 10^4$ beads/tube, in 500 μl of DI Water).

A fluorescence microscope (Leica, Leitz DMRBE) was used to analyse the fluorescent fine particle concentrations in the cobble biofilm samples. The flow cytometer could not be used on these samples because of interference by high concentrations of background organic debris and fine particulate matter. Fluorescent particle concentrations were measured in these samples by direct count on a 1 mL gridded microscope slide (Sedgewick-Rafter cell) under 50× magnification. The samples were first homogenized by vortexing. The middle 20 cells on the gridded slide were counted for all samples. Where necessary, samples were diluted to yield no more than 100 fluorescent particles per grid cell on the counting slide.

Biomass was scraped from each cobble and the ash-free dry mass (AFDM) method was followed (American Public Health Association, 1998) to estimate the total biomass as organic matter in the sample. Each sample was placed in pre-weighed aluminium weigh pans and placed in a 104°C drying oven for at least 24 hr to reach a dry stable weight. Total particulate matter (TPM) is defined as the dry mass of the sample. The samples were then placed in the muffle furnace at 400°C for a minimum of 6 hr, the furnace turned off and the pans were allowed to cool for 30 min. The pans were then placed back in a desiccator until the dry weight was stabilized. Seven cobbles at the restored reach and three cobbles in the control reach were below the limit of detection (1 mg) and are not included within the analysis.

The particle size distribution of remobilized sediments in the water samples was measured by an EYE TECH laser particle analyser (Ankersmid, Eindhoven, Netherlands).

## 2.5 | Modelling reach-scale fine particle transport, retention and remobilization

We modelled the solute and fine particle breakthrough curve data using a mobile–immobile model, previously applied to solute and fine particle transport in rivers (Drummond et al., 2017; Drummond, Aubeneau, & Packman, 2014). Here we provide a brief review of key equations and model parameters. The mobile–immobile model is governed by advection and dispersion processes convolved with a memory function to represent storage in the system (Boano et al., 2014):

$$\frac{\partial C(x,t)}{\partial t} = \int_0^t M(t-t')\left[-v\frac{\partial C(x,t')}{\partial x} + D\frac{\partial^2 C(x,t')}{\partial x^2}\right]dt' \qquad (1)$$

where $C$ [M L$^{-3}$] is in-stream concentration, $t$ [T] is the elapsed time, $t'$ [T] is a dummy time variable, $x$ is downstream distance [L], $M(t)$ [T$^{-1}$] is the memory function, and $v$ [L T$^{-1}$] and $D$ [L$^2$ T$^{-1}$] are the velocity and dispersion coefficient in the stream. The memory function (Equation 2) is dependent on the overall residence time distribution in the stream, $\psi_i$ [T$^{-1}$], where subscript $i$ represents $S$ and $P$ for solutes and fine particles, respectively. The Laplace transform of the memory function $M(t)$ is:

$$\tilde{M}(u) = u\bar{t}\frac{\tilde{\psi}_i(u)}{1-\tilde{\psi}_i(u)} \qquad (2)$$

where $u$ [T$^{-1}$] is the Laplace variable and $\bar{t}$ is the average travel time in the reach, defined as the stream reach length divided by the mean water velocity ($v$). $\psi_i$ [T$^{-1}$] is defined by the residence time distribution in the mobile region (water column), $\psi_0$ [T$^{-1}$], the rate of exchange from the water column to the immobile region, $\Lambda_i$ [T$^{-1}$], and the residence time distribution in the immobile region, $\varphi_i$ [T$^{-1}$]. In Laplace space:

$$\tilde{\psi}_i(u) = \tilde{\psi}_0[u + \Lambda_i - \Lambda_i\tilde{\varphi}_i(u)] \qquad (3)$$

Here, we assume that a single distribution $\psi_0$ characterizes the transport of solutes and fine particles in the water column, since these materials should be transported very similarly in the water column. We take this as an exponential distribution $\psi_0(t) = e^{-t}$ (Boano, Packman, Cortis, Revelli, & Ridolfi, 2007).

In this study, we define the immobile region as all stream storage areas, including the benthic, hyporheic, and slower-moving surface storage zones. We assume that solutes and tracer particles are transported identically in the stream water column owing to the very small settling velocity of fine particles. For the same reason, we assume that delivery of fine particles to transient storage areas is controlled purely by advective exchange and that gravitational settling is negligible. In this case, hyporheic exchange of solute and fine particles is also similar, and $\Lambda_S \approx \Lambda_P$. Based on prior investigations of solute and fine particle dynamics in rivers (Boano et al., 2014; Drummond et al., 2015, 2017), we assumed a power-law residence time distribution within the immobile region, $\varphi_S(t) \sim t^{-(1+\beta_S)}$ for $0 < \beta_S < 1$.

The residence time distribution for particles, $\varphi_P$, describes both the delay in downstream transport that results from particles entering the immobile regions, and particle immobilization-remobilization within these regions (e.g., from reversible deposition, filtration, and attachment). The residence time distribution for particles within Equation (3), $\varphi_P$, describes the immobilization of particles within the immobile region. In Laplace space:

$$\tilde{\varphi}_P(u) = \tilde{\varphi}_S[u + \Lambda_{IP} - \Lambda_{IP}\tilde{\varphi}_{IP}(u)] \tag{4}$$

where $\tilde{\varphi}_S$ is the solute residence time distribution in the immobile region, $\Lambda_{IP}$ is the rate of fine particle immobilization within the immobile region, and $\tilde{\varphi}_{IP}$ is the particle residence time distribution in the immobile region (Drummond et al., 2017; Drummond, Aubeneau, & Packman, 2014). The residence time distribution of fine particles in the immobile region is also represented as a power-law distribution $\varphi_{IP}(t) \sim t^{-(1+\beta_{IP})}$, for $0 < \beta_{IP} < 1$. Thus, the model accounts for both fine particle transport into and out of storage areas such as the hyporheic zone and low-velocity surface storage zones, and immobilization and remobilization within these regions.

In summary, the key parameters that describe the mobile zone (i.e., water column) of the model are the in-stream velocity, $v$ [L T$^{-1}$] and dispersion, $D$ [L$^2$ T$^{-1}$]. The rate of exchange of solutes and particles from the water column to immobile regions (i.e., streambed sediments, surface pools) is set by $\Lambda_S$ [T$^{-1}$]. The time solutes and particles spend in the immobile zone is controlled by the following parameters: (a) the power-law residence time distribution of solute within the immobile zone, set by the power law slope, $\beta_S$, (b) the rate of fine particle immobilization with the immobile zone, $\Lambda_{IP}$, and (c) the power-law residence time distribution of particles in the immobile zone, set by the power-law slope, $\beta_{IP}$.

Following the fitting procedure outlined in Drummond, Schmadel, Kelleher, Packman, and Ward (2019), we performed several computational experiments with simulations and parameter sets constrained to match the conservative solute and fine particle breakthrough curves. We sampled the parameter space using a Latin Hypercube approach (N = 27,000; e.g., Kelleher et al., 2019). The Balanced mean square error ($\hat{\theta}$; Bottacin-Busolin, Marion, Musner, Tregnaghi, & Zaramella, 2011) objective function was calculated for each simulation as:

$$\hat{\theta} = \left(\frac{1}{n}\left[\frac{\sum_{i\subset n_A}(C_{\mathrm{sim},i}(\theta)-C_{\mathrm{obs},i})^2}{(\max(C_{\mathrm{obs}})-\min(C_{\mathrm{obs}}))^2}\right] + \left[\frac{\sum_{i\subset n_B}(\log(C_{\mathrm{sim},i}(\theta))-\log(C_{\mathrm{obs},i}))^2}{(\max(\log(C_{\mathrm{obs}}))-\min(\log(C_{\mathrm{obs}})))^2}\right]\right)^{1/2} \tag{5}$$

where the total number of observations, $n$, is the sum of $n_A$ and $n_B$, defined as the number of observations above and below a threshold concentration, respectively. A 20% of the peak threshold concentration has been shown to provide a balanced weight that considers both the peak and tail of the breakthrough curve (Bottacin-Busolin et al., 2011). We assessed parameter uncertainty and model performance comparing the top 1% of all simulations for the balanced objective function, with this threshold corresponding to the best-fit, behavioural set of parameter-objective function combinations. Following Drummond et al. (2019), we first calibrated the model using the full range of model parameters. Then to improve the model fit and parameter interpretability, we constrained ranges for $v$ and $D$, each parameter evaluated separately, from the confidence intervals from the averaged solute and particle fit (i.e., ± the standard deviation of the best 0.05% fits) and kept all other parameter ranges wide.

In-stream data at the log in the restored reach (S-Log) was not fit with the model, as the model requires that the in-stream sampling site is well mixed (i.e., in the channel thalweg), whereas S-Log is a habitat-scale measurement showing the potential for in-stream storage in the restored reach near the added wood.

## 2.6 | Calculations of reach-scale fine particle transport, retention and remobilization

As an estimate of the short-term retention of fine particle tracers, we calculated $RT_{\max}$ as the latest time the simulated fine particle tracer was detected at the sampling site, set as the time the in-stream concentration returned to 1 # mL$^{-1}$. This value represents the timeframe for the short-term resuspension of fine particles, while the remaining particles are assumed to stay immobilized for much longer. Long-term retention of solute and fine particle tracers in the study reach was determined by comparing integrated mass ($\int C(t)Q(t)dt$) at the in-stream sampling sites, where C(t) is the modelled in-stream concentration and Q(t) is the discharge. The percent difference of mass recovered ($\%_{\mathrm{IMM}}$) was calculated between S1 and S2 in each reach and also normalized by the reach length between S1 to S2 for a more direct comparison of the percentage of particles immobilized per meter ($\%_{\mathrm{IMM}}/m$).

## 2.7 | Statistical analysis

We used a Wilcoxon Kruskal–Wallis test to examine whether the number of remobilized particles per volume differed between the control and restored reaches. We used a non-parametric test because our data set was relatively small and often not normally distributed.

We examined the relationship between biomass on cobbles and the fluorescent fine particles deposited on each individual cobble by applying bivariate linear regression models. Fits were performed by ordinary least squares assessed as goodness of fit ($r^2$; Zar, 2010). We examined the influence of the restoration on model transport parameters by conducting a one-way analysis of variance (ANOVA) comparing sampling sites (Control S1, Control S2, Restored S1 and Restored S2). We used post hoc Tukey's test to identify which groups differed from each other (Zar, 2010). In all cases, differences were considered statistically significant if $p < .05$. Statistical analysis was performed with Matlab software version R2019a (The MathWorks, Inc., Natick, MA).

## 3 | RESULTS

### 3.1 | Reach-scale fine particle transport and retention

The mobile-immobile model was able to accurately characterize the solute and fine particle transport and retention within the control and restored reaches and extend the data beyond the measured observations (Figure 3). Best-fit model parameters for Site 1 and 2 in the control and restored reaches are shown in Table 1. Velocity varied between the sampling sites, increasing with distance downstream. Notably, both the exchange rate of solute and particles into transient storage areas ($\Lambda_S$) and the power-law slope of solute in these regions ($\beta_S$), which controls the rate of solute and fine particle transport and extent of retention within these slower moving regions, was different at S2 in the restored reach downstream of the wood additions. A lower $\beta_S$ indicates increased solute retention, with a slower release of solutes back into the water column as compared to higher $\beta_S$ values observed at the other sampling sites. Although $\Lambda_S$ was on average greater at Control S1, this value was not well constrained as shown by the wide confidence intervals, while $\Lambda_S$ at Restored S2 was higher than Control S2 and Restored S1 with a very narrow confidence interval, suggesting increased reach-scale exchange at this site, likely due to the presence of added wood ~6 m upstream of this sampling location. The particle-specific transport parameters ($\Lambda_{IP}$, $\beta_{IP}$) did not differ between the sampling sites (Table 1). Together, these results suggest that solute transport and retention was affected by the wood additions, and solute exchange rates and retention times were the main control for fine particle retention in both reaches.

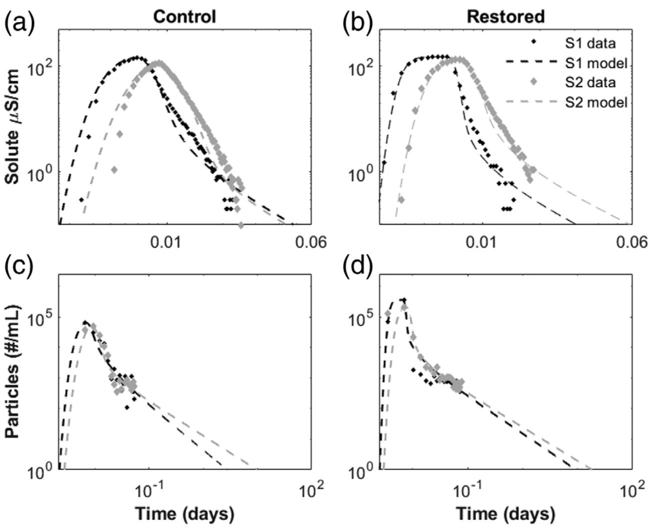


**FIGURE 3** Reach-scale measurements of solute and fine particle transport and retention. Tracer breakthrough curves and model fits of solute (top row) and fine particles (bottom row) at S1 and S2 in the control (AC) and restored (BD) reaches shown in log space

From the model simulations with breakthrough curve tails extended to background concentrations, in-stream solute recovery at the downstream site was 101.8 and 98.3% for the control and restored reach, respectively. The recovery over 100% in the control reach represents a reasonable low level of error associated with using different sensors between the sites. Increased immobilization of fluorescent fine particles was found in the restored compared to the control reach. Specifically, extending the breakthrough curves beyond the end of the sampling period until the concentrations reached 1 #/mL fluorescent particles, 1.5 and 31.6% of the injected particles were retained within the control and restored reach, respectively (Table 2). When retention was normalized by reach length ($\%_{IMM}$/m) there was still increased retention within the restored vs. control reach (Table 2). Furthermore, $RT_{max}$ and $RT_{max}/t_{peak}$ that both reflect the short-term retention times of fine particles in the reaches was greater within the restored vs. control reach (Table 2).

### 3.2 | Habitat-scale fine particle transport, retention and resuspension

Increased solute and fine particle concentrations and residence times were observed directly behind the channel spanning log (Figure 4). This increased heterogeneity in flowpaths and retention times in the

**TABLE 1** Best-fit parameters and associated confidence intervals calculated as ± the standard deviation of the best 0.05% fits

| | $v$ (m/s) | $D$ (m$^2$/s) | $\Lambda_S$ (1/s) | $\beta_S$ | $\Lambda_{IP}$ (1/s) | $\beta_{IP}$ |
|---|---|---|---|---|---|---|
| Control S1 | 0.033 ± 0.0032[a] | 0.007 ± 0.0029[a] | 0.031 ± 0.061[a] | 0.73 ± 0.10[a] | 0.45 ± 0.23[a] | 0.62 ± 0.18[a] |
| Control S2 | 0.048 ± 0.0026[b] | 0.045 ± 0.012[b] | 0.0040 ± 0.019[ab] | 0.60 ± 0.11[a] | 0.86 ± 0.26[a] | 0.32 ± 0.084[a] |
| Restored S1 | 0.074 ± 0.0029[c] | 0.008 ± 0.0055[a] | 0.0049 ± 0.023[ab] | 0.60 ± 0.17[a] | 0.31 ± 0.30[a] | 0.40 ± 0.12[a] |
| Restored S2 | 0.094 ± 0.0025[d] | 0.039 ± 0.0046[c] | 0.0089 ± 0.0042[b] | 0.57 ± 0.084[b] | 0.12 ± 0.19[a] | 0.26 ± 0.10[a] |

*Note:* For each variable, different letters represent significant differences between groups (post hoc Tukey's test after one-way ANOVA, $p < .05$).

**TABLE 2** Reach-scale particle parameters for the restored and control reaches

| | Control, S1 | Control, S2 | Restored, S1 | Restored, S2 |
|---|---|---|---|---|
| Retained particles between S1 to S2, $\%_{IMM}$ | 1.48 | | 31.59 | |
| Retained particles per meter ($\%_{IMM}$/m) | 0.06 | | 1.61 | |
| Maximum retention time, $RT_{max}$ (days) | 2.78 | 9.70 | 9.35 | 18.23 |
| Time to peak, $t_{peak}$ (days) | 0.0068 | 0.0088 | 0.0063 | 0.0075 |
| $RT_{max}/t_{peak}$ | 407 | 1,107 | 1,477 | 2,442 |

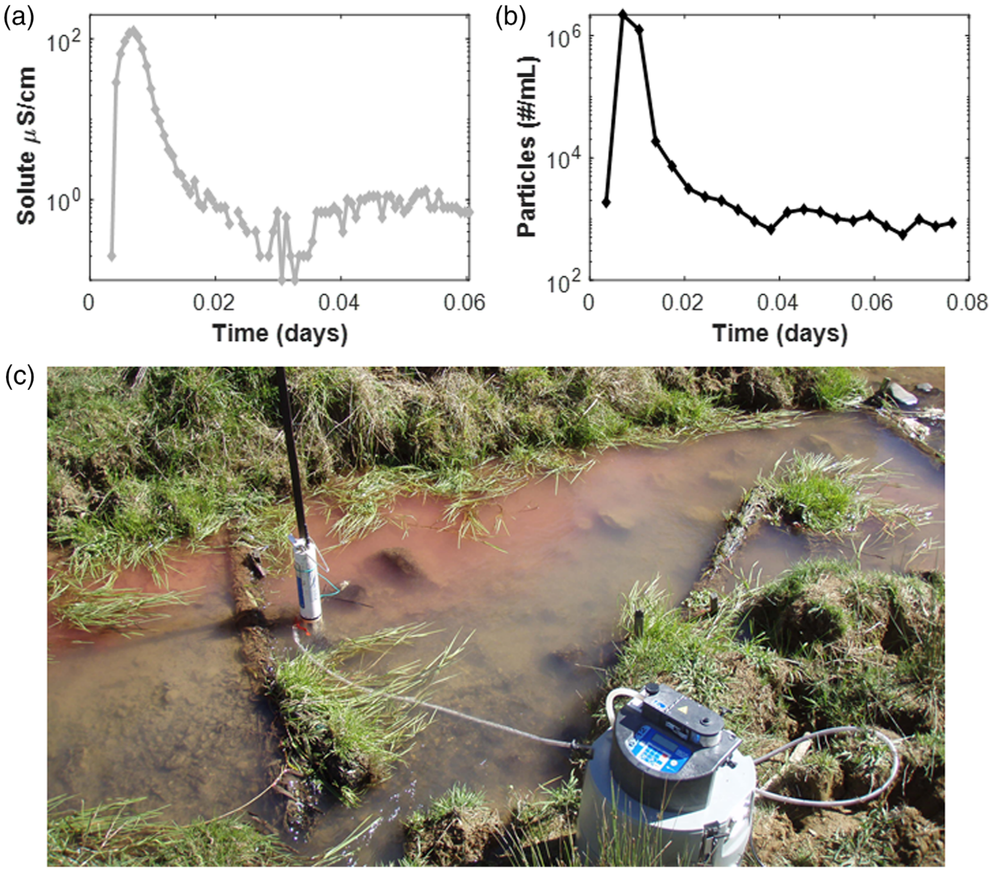


**FIGURE 4** Habitat-scale measurements of (a) solute and (b) fine particle transport and retention at S-Log, immediately downstream of an emplaced log in the restored stream. (c) Photo at S-Log 14 minutes after the start of the injection, (i.e., 9 minutes after the end of the 5-minute injection) showing extended surface storage near S-Log

restored reach was represented by the much longer tailing behaviour at S-Log, relative to locations farther from the wood (S1 and S2, Figure 3). The breakthrough curve data at S-Log matched the visual observations of pink tracer particles near the wood 9 min after the end of the 5-min injection (Figure 4b,c), while the remainder of the water column was without visible tracer indicating that concentrations were higher near the log.

Fluorescent fine particles were observed in all biofilms on cobbles in both the restored and control reach. Although the average biomass on cobbles was 0.15 mg/cm$^2$ in both the control (0.15 ± 0.072 mg/cm$^2$) and restored reach (0.15 ± 0.16 mg/cm$^2$), more heterogeneity in biomass and particle counts on cobbles was observed in the restored reach, shown by the increased range in values (Figure 5a,b). There was a linear relationship ($r^2$ = .54, $p$ < .05) between biomass and fluorescent fine particle deposition on cobbles (Figure 5b). In the restored reach, fine particle deposition was greatest in the biomass on the cobbles directly upstream of the channel-spanning log (Log 1, Figure 5c).

The number of remobilized particles was significantly higher in the control vs. restored reach ($p$ = .01, Figure 6), suggesting that more particles are easily resuspended from the control reach following a bed mobilizing disturbance. The $d_{50}$ of the resuspended sediment was 6.33 ± 0.70 μm and 4.15 ± 0.44 μm in the control and restored reaches, respectively, which is similar to the size of the injected fluorescent fine particles (mean diameter ~4 μm).

## 4 | DISCUSSION AND CONCLUSIONS

Increased short-term retention of tracer particles was observed in the restored reach compared to the control reach in both reach-scale and

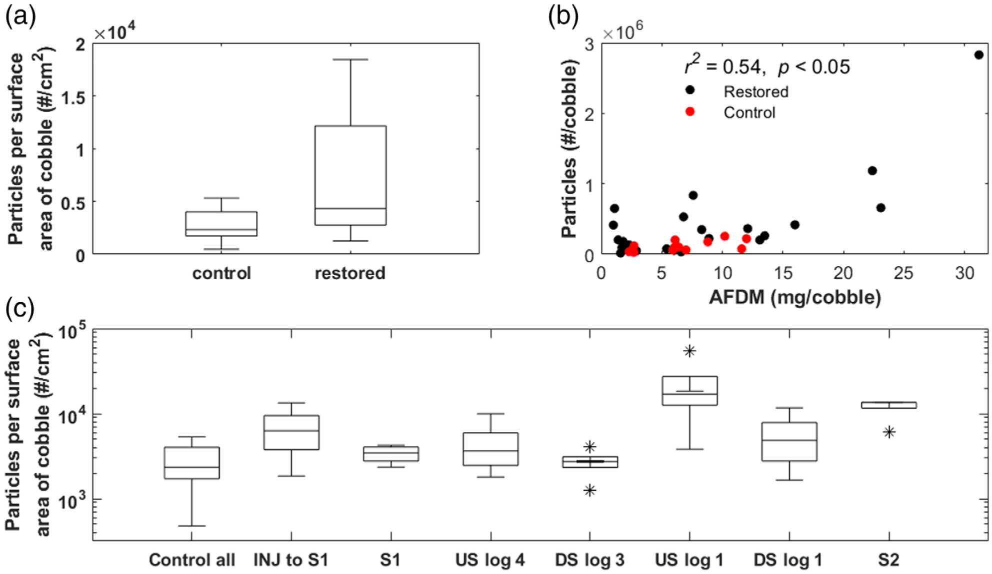


**FIGURE 5** Habitat-scale measurements of fine particles attached to biofilm on cobbles (a) comparison between the control and restored reach, (b) related to the biofilm biomass associated with each individual cobble ($r^2$ = .54, $p$ < .05), (c) shown by individual site ($n$ = 4) with all control sites together ($n$ = 12)

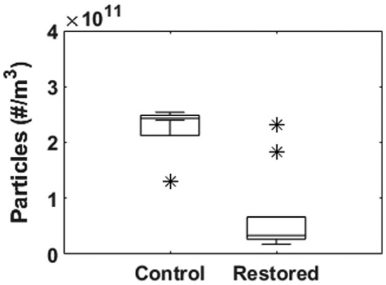


**FIGURE 6** Habitat-scale measurements of remobilized particles from the sediment bed to the water column after a disturbance in both the restored ($n$ = 9) and control ($n$ = 4) reach normalized by the volume of sediment displaced within the stream

habitat-scale measurements. The differences in reach-scale short and long-term particle retention in the restored reach, shown by higher $RT_{max}$ and $\%_{IMM}$, respectively, reflect the greater hydraulic diversity generated by the addition of the wood. Added wood increased heterogeneity in stream habitats and flowpaths by increasing solute and fine particle retention locally near the wood. There was also increased heterogeneity in the habitat-scale measurements of fine particle deposition on cobbles, shown by a wider range of particle counts in the restored reach. The control reach is a fairly uniform habitat with few flow obstructions, but the wood additions increased hydraulic heterogeneity, generating more low velocity depositional habitats in some parts of the reach nearer to the wood. Increased fine particulate organic matter has been found to be positively related to habitat heterogeneity (Frainer, Polvi, Jansson, & McKie, 2018). This can be partly explained by the increased hyporheic exchange near wood and increased hydraulic roughness that reduces bed shear stress and leads to less remobilization and longer retention around the wood (Briggs et al., 2012; Krause et al., 2014). Our results agree with these previous observations, with increased solute exchange and retention in the reach with added wood, shown by higher $\Lambda_S$ and lower $\beta_S$ values at Restored S2. Although the tracer particles only represent a small range of sizes and densities of natural particles in streams, the high rate of exchange and retention of these small particles demonstrate the importance of hyporheic exchange within this stream. Therefore, particles that also transport with solute, likely all particles <1 mm regardless of particle density (Drummond, Aubeneau, & Packman, 2014), will be influenced by wood additions and transport similarly within this stream. However, larger and denser particles than those used in the study but still <1 mm are even more likely to immobilize and be retained within the sediments, as they will be preferentially immobilized due to gravitational settling and filtration within sediment porewaters (Bradford, Yates, Bettahar, & Simunek, 2002; Jin et al., 2019).

Increased retention of fine particles occurred very near the emplaced logs. These findings agree with previous studies showing that sediment and organic matter deposition is a localized effect near large wood, which increases the heterogeneity in fine particle deposits within the stream. Accumulation of organic material promotes the regeneration of vegetation (Osei, Gurnell, & Harvey, 2015) and influences biogeochemical reactions (Briggs et al., 2013). Channel-spanning logs were the most effective at retaining fine particles, demonstrating that geometries and blockage ratio are important for fine particle deposition around wood, as has been observed for deposition of coarser organic matter and sediments (Gippel, O'Neill, Finlayson, & Schnatz, 1996; Kail, Hering, Muhar, Gerhard, & Preis, 2007). Increased accumulation of particulate organic matter also occurs by increased retention of coarser materials near the wood and subsequent breakdown into finer materials. However, our injection results demonstrate that fine particles are quickly immobilized and retained for hours after an addition.

More particle retention in the restored reach can partly be explained by less particle remobilization after a bed disturbance, which was observed in this study after stirring bed sediments. Natural spates and high flow events will only partially remobilize particles retained in streambed sediments (Drummond et al., 2014; McKergow & Davies-Colley, 2010), whereas our disturbance represented the extreme case of complete bed remobilization down to the depth the sediments were stirred. Still, compared to the reach-scale results of less overall retention in the control reach, the fact that the particles were more easily remobilized from the control reach demonstrates the loose attachment of the particles to the sediment matrix in this reach as compared to the control reach. Although the initial immobilization of fine particles occurred near to the log, previous results have demonstrated the slow and continuous reworking of fine particles after initial deposition (Gartner, Renshaw, Dade, & Magilligan, 2012; Harvey et al., 2012). The retention near the logs and slow transport of fines within the reach can lead to filling of pore spaces within the sediment matrix, subsequently increasing the colonizable surface area, and thus biomass, which can stabilize sediments and thereby decrease remobilization during flow disturbances (Mendoza-Lera & Datry, 2017; Roche et al., 2017; Vignaga et al., 2013). Thus, these depositional habitats can contribute to increased areal coverage of fine sediment over time via infilling of interstitial space and then development of surface cover. Furthermore, the mean size of easily resuspended particles following a bed mobilizing disturbance was $\sim$5 μm, similar to the fine particle tracer ($\sim$4 μm). Mobile benthic and hyporheic material is generally remobilized as soon as bed sediment transport occurs (Gartner et al., 2012; Stewardson et al., 2016). Therefore, these results demonstrate that very fine particles in the size range of $\sim$5 μm easily deposit and resuspend and are very dynamic within streams, potentially having a greater longitudinal footprint than other particle sizes.

Overall, our results show that the wood generated larger and more stable transient storage zones, which have the potential to act as biogeochemical hotspots that may increase nutrient retention and contribute to stream productivity. Biogeochemical reactions can be affected by wood additions at both short and long timescales. For example, at short timescales, the increased solute flux from wood additions may lead to increased reaction rates within these areas (Reeder et al., 2018). At the longer timescale, fine sediments can serve as a time-release capsule for nutrients and carbon over months, fuelling biochemical transformations (Larsen & Harvey, 2017). In fact, particulate organic carbon has been shown to directly influence nitrogen processing in streams (Stelzer, Thad Scott, Bartsch, & Parr, 2014). This is important for wood additions, as they yield a higher likelihood of retention of particulate organic matter, both leaves and finer particulate organic matter, that can help stimulate biogeochemical activity in these patchy regions. Moreover, without long-term retention of particulate organic carbon, carbon cycles may be disrupted (Larsen & Harvey, 2017). Therefore, even if restoration increases hyporheic exchange, this alone will not lead to increased retention of fine particles if there is also the simultaneous rapid remobilization of fines, as was found in a stream restored with gravel vanes (Drummond, Larsen, González-Pinzón, Packman, & Harvey, 2018).

This study reflects an engineered reach with localized wood additions, whereas in more natural conditions the wood may be distributed throughout the reach. However, our results demonstrate the localized effect of added wood, which is expected regardless of the distribution, with more wood leading to an increased reach-scale change in fine particle accumulation. However, more studies are needed to confirm this hypothesis and to assess fine particle retention in more natural stream systems. A previous study within our study catchment showed that hyporheic exchange flow was stronger in a stream where no wood was present, but more fine sediments and higher densities of invertebrates were found near large wood (Wagenhoff & Olsen, 2014). Wagenhoff and Olsen (2014) concluded that wood additions may not be an effective rehabilitation tool to improve hyporheic habitat with a focus on sediment depths of 10–30 cm. However, an alternate conclusion is that wood may improve hyporheic habitat in the streambed sediments by retaining fine particles in patchy refuge sites near the sediment–water interface, providing improved habitat around wood. Therefore, instead of only focusing on increasing hyporheic exchange, the balance between immobilization and remobilization of fine particles is the best measure to consider during restoration of stream ecosystems. Overall, we demonstrate that wood additions, a cost effective and relatively simple restoration method, increased retention of solutes and fine particles in patchy areas surrounding wood and can lead to long-term fine particle retention.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data used in this study is provided online at https://doi.org/10.6084/m9.figshare.11965512.

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